

## **Auditory Weighting Functions and Frequency-Dependent Effects of Sound in Bottlenose Dolphins (*Tursiops truncatus*)**

James J. Finneran

Space and Naval Warfare Systems Center Pacific  
Biosciences Division, Code 71510  
53560 Hull Street  
San Diego, CA 92152

phone: (619) 767-4098 fax: (619) 553-0899 email: [james.finneran@navy.mil](mailto:james.finneran@navy.mil)

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### **LONG-TERM GOALS**

The long term goal of this effort is to develop meaningful auditory weighting functions for marine mammals. These weighting functions would improve assessments of the effects of anthropogenic sound by emphasizing frequencies to which animals are most sensitive and de-emphasizing those to which they are not.

### **OBJECTIVES**

The objective of this effort was to develop auditory weighting functions for bottlenose dolphins with normal hearing and high-frequency hearing loss. The weighting functions were defined by measuring subjective loudness and temporary threshold shift (TTS) as functions of the sound frequency.

### **APPROACH**

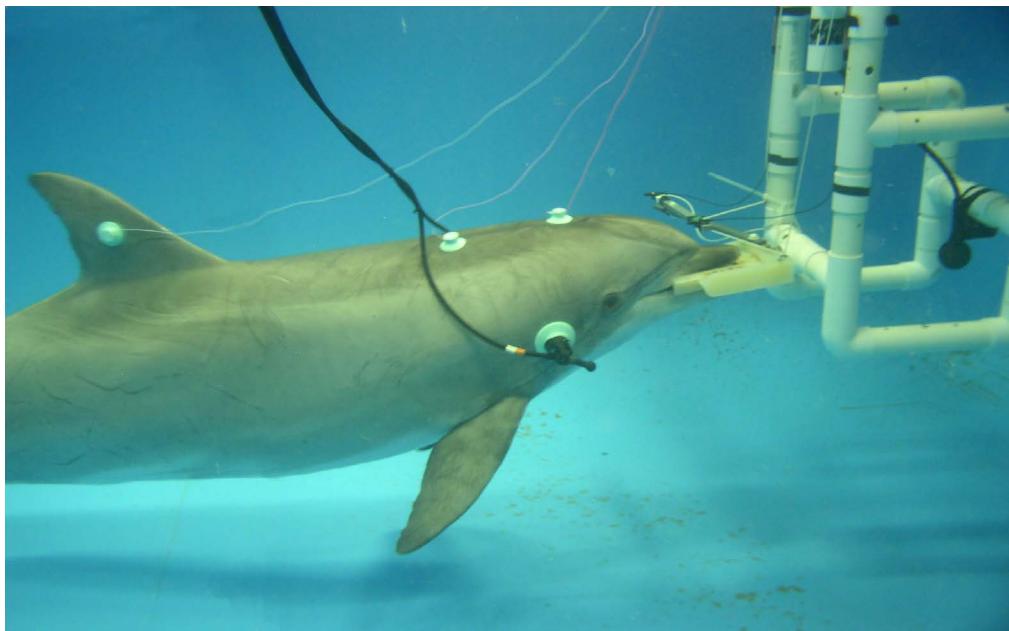
TTS is defined as the difference between hearing thresholds measured before and after an intense (fatiguing) sound exposure. Hearing thresholds were estimated using either a behavioral response paradigm, where the subject is trained to perform a specific action when it hears a test tone, or an electrophysiological method, where auditory evoked potentials (AEPs) were measured in response to test tones. Hearing tests are typically conducted  $\sim$ 1/2-octave above the exposure frequency, where the largest TTS is expected.

Behavioral methods developed at the Navy Marine Mammal Program (MMP) allowed thresholds to be obtained within four minutes of intense sound exposures. This was accomplished using computer-controlled stimulus presentations, recording acoustic responses emitted by the subject in response to those stimuli, and presenting multiple trials before subject reinforcement. Dolphins typically produce an acoustic response (a whistle or burst pulse) within a few hundred milliseconds of tone onset, allowing a rapid pace of stimulus presentation and fast threshold estimates. A modified up/down descending staircase technique was used to adjust the stimulus level in an adaptive fashion from one trial to the next and bracket the threshold.

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Electrophysiological thresholds were estimated by measuring a type of AEP called an auditory steady state response (ASSR). Hearing tests are conducted underwater using a stimulus projected in the direct field (not via a “jawphone”). A statistical test (magnitude-squared coherence) was used to objectively determine the presence or absence of AEPs in response to stimuli at different levels. Thresholds were based on the lowest detectable response with a 1% probability of false detection.

Subjects were trained to wear suction cup-mounted hydrophones during the fatiguing sound exposures to allow estimates of the received sound levels regardless of subject location. Pure-tone exposures were characterized by the average sound pressure level (SPL), sound exposure level (SEL), and exposure duration. Tests were conducted in a quiet, above ground test pool.



***Figure 1. A dolphin subject in the pool during a TTS experiment. Suction cup-mounted hydrophones placed near the ears are used to record the sound levels during the fatiguing sound exposure. Surface electrodes embedded in small suction cups placed on the head and back are used to measure AEPs.***

Equal loudness tests used a loudness comparison method where the subject was presented two sequential tones. The subject was trained to whistle if the first tone was perceived louder than the second and to produce a burst pulse or “buzz” response if the second tone was louder than the first. The majority of trials featured stimulus pairs for which the loudness relationship between the two tone pairs was known, for example two tones at the same frequency but with different SPLs. The subject’s performance on the “known” trials allowed his performance to be tracked within each session.

Approximately 30% of the trials were probe trials, consisting of a reference tone, whose frequency and SPL were fixed, and comparison tone, whose frequency is fixed within a session but whose SPL varies. The order in which the reference and comparison tones were presented was balanced within each session. The subject’s responses to the probe trials were analyzed using nonlinear regression to derive curves relating the probability of the comparison tone being perceived louder for each comparison tone frequency. The 50% point then represented the SPL at which the comparison tone

was equally loud as the reference. This method is similar to methods used to derive equal loudness curves in humans.

James Finneran served as the PI and project manager, developed the hardware and software for AEP and behavioral hearing tests and the loudness comparison tests, analyzed the acoustic and threshold data, performed the TTS mathematical modeling, and derived the auditory weighting functions. Carolyn Melka served as the technical coordinator for the threshold, TTS, and equal loudness tests conducted in the pool, conducted the daily experiments, calibrated the sound system, and analyzed/archived the resulting data.

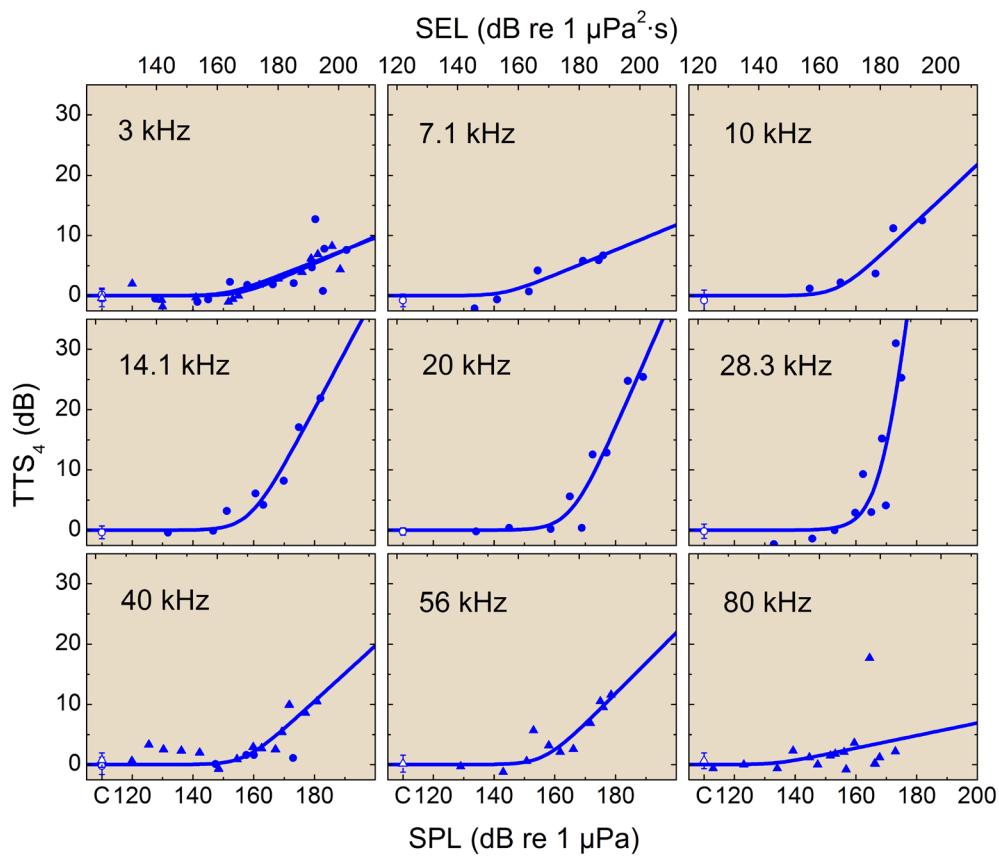
## WORK COMPLETED

We completed a total of 98 control sessions and 73 fatiguing exposure sessions with the dolphin BLU (age 44 y). Fatiguing exposure durations were 16 s; exposure frequencies ranged from 3 kHz to 40 kHz. Frequencies above 40 kHz were not tested because the affected frequency range would have been beyond the upper limit of BLU's hearing.

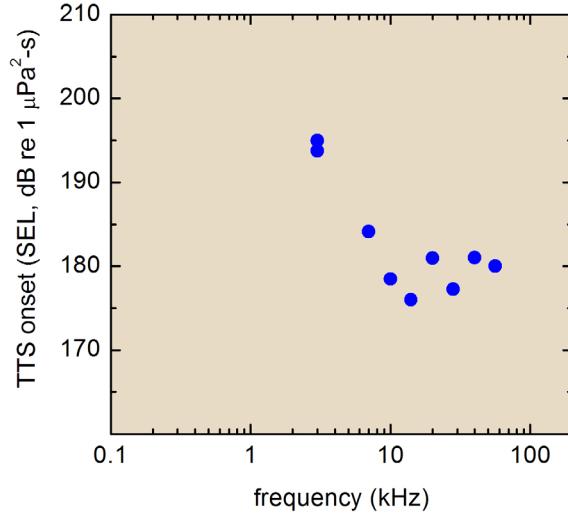
We completed a total of 237 equal loudness sessions (15 391 trials) with the dolphin TYH (age 28 y). The reference tone frequency was 10 kHz, with SPLs of 90, 105, and 115 dB re 1  $\mu$ Pa. Comparison frequencies ranged from 2.5 to 113.1 kHz. At each frequency, we obtained between 73 and 1414 individual data points. We also completed a total of 38 control sessions and 35 fatiguing exposure sessions with TYH. Fatiguing exposure durations were 16 s; exposure frequencies ranged from 3 kHz to 80 kHz.

## RESULTS

TTS measurements in BLU and TYH at various frequencies across their range of hearing allowed us to define the growth and onset of TTS for exposures from 3 to 56 kHz. These data (Figs. 2 and 3) reveal substantial differences between onset-TTS levels and TTS growth rates. This means TTS will occur at lower exposure levels, and increase more rapidly with increasing exposure level, as frequencies increase beyond 3 kHz. Consequently, acoustic impact thresholds based on 3-kHz data are not appropriate for higher frequency exposures – they will underestimate the effects. In BLU, exposures at 40 kHz did not produce TTSs at or above the exposure frequency presumably due to the subject's existing high-frequency hearing loss.

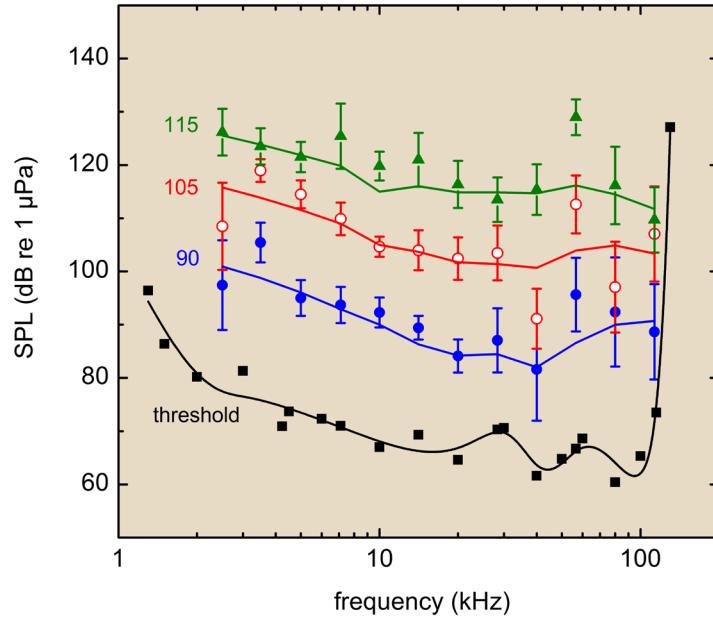


**Figure 2. TTS as a function of SPL and SEL for 16-s exposures at 3, 7.1, 10, 14.1, 20, 28.3, 40, 56, and 80 kHz in the dolphins BLU and TYH. Hearing was tested 1/2-octave above the exposure frequency using behavioral methods. As the exposure frequency increased, the growth rates also increased, up to 28.3 kHz**

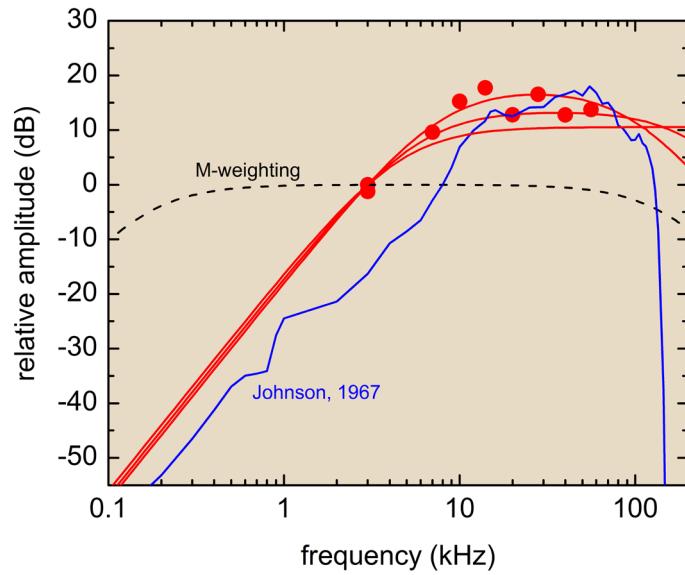


**Figure 3.** TTS onset (i.e.,  $TTS_4 = 6 \text{ dB}$ ) as a function of exposure frequency in BLU and TYH. The exposure level required to cause TTS decreases up to  $\sim 10 \text{ kHz}$ , then remains relatively constant up to  $56 \text{ kHz}$ .

Figure 4 shows equal-loudness contours measured in the dolphin TYH. The data obtained from this study represent the first direct measurement of equal-loudness curves in any animal. The existence of equal loudness contours means that auditory weighting functions can now be developed in a manner directly analogous with the approach used for humans. Figure 5 shows auditory weighting functions derived from the dolphin equal loudness contours along with the Southall *et al.* mid-frequency cetacean weighting function, the TTS susceptibility data, and an estimate of dolphin auditory sensitivity. The dolphin weighting function shows remarkable agreement to the experimental TTS onset data and is similar, though higher (i.e., predicts greater susceptibility), than the auditory sensitivity. Above 3 kHz, the dolphin weighting function predicts a larger effect from noise than the M-weighting function for mid-frequency cetaceans. At the lower frequencies, the weighting function shows an increasing departure from the Southall *et al.* mid-frequency weighting function, greater than 40 dB at a few hundred hertz.



**Figure 4.** Equal loudness contours passing through 10 kHz at 90, 105, and 115 dB SPL. The numbers with each series indicate the 10-kHz reference tone level, in dB re 1  $\mu$ Pa. The equal-loudness contours tend to parallel the audiogram (the hearing threshold as a function of frequency), but diverge at the highest frequencies.



**Figure 5.** Auditory weighting functions derived from the dolphin equal loudness contours (red lines) fit the TTS onset data (symbols), are similar to the auditory sensitivity curves, and predict much greater sensitivity to high frequency sounds than the M-weighting function proposed by Southall et al. (2007).

## **IMPACT/APPLICATIONS**

The observed differences between TTS onset at 3–56 kHz will affect the manner in which Navy predicts auditory effects of high-frequency sonars on wild marine mammals. Previously, onset-TTS data from dolphins tested at mid-frequencies (primarily 3 kHz) were used to make predictions at all other frequencies. Data at higher frequencies, arising from this study, are now used to create frequency-dependent estimates for onset-TTS (i.e., TTS weighting functions) that are more accurate than previous estimates.

Similarly, the equal loudness data show the relationship between the frequency of sound and the subjective loudness of the sound. Weighting functions created from these data may be more appropriate to assessing behavioral effects of sound, under the assumption that the behavioral reactions of animals are more strongly related to the *loudness* of a sound compared to the *SPL* of the sound.

## **TRANSITIONS**

Data resulting from this project have been presented at scientific conferences, briefed to ONR, NMFS, and CNO N45, and published in peer-reviewed scientific journals. The TTS data are often used in environmental assessments and impact statements that must be prepared for weapons systems development, surveillance systems development, quality assurance tests, oceanographic research, and training exercises. The TTS data that have been collected to date have been used extensively by Navy environmental analysts and have been used to derive acoustic impact criteria for various EAs and EISs, including the SEAWOLF Shock Trial, the WINSTON CHURCHILL Shock Trial, MESA VERDE (LPD 19) Shock Trial, USWTR, HRC, SOCAL, and AFAST EISs. These data have also affected decision making on naval exercises such as RIMPAC and provided the basis for deconfliction guidelines for US Navy Marine Mammal Systems operating near active acoustic sources. The TTS data are used by not only the US Navy, but also by various NATO allies and the seismic industry for predicting and mitigating effects of sonars and explosives on marine mammals.

The AEP system software developed at the Navy MMP (called EVREST — the Evoked Response Study Tool) has been shared with other researchers conducting AEP measurements, including those at UC Santa Cruz (Colleen Reichmuth and Marissa Ramsier), University of South Florida (David Mann), and the Pennsylvania State University Applied Research Lab (Mardi Hastings). The system has been used to test the hearing of a variety of animals, including invertebrates, fish, pinnipeds, cetaceans, and primates.

## **RELATED PROJECTS**

“Temporary threshold shift (TTS) in odontocetes in response to multiple airgun impulses,” is a related project funded by the International Association of Oil and Gas Producers, Joint Industry Project (JIP). This effort employs techniques and equipment for behavioral and AEP hearing tests developed under previous ONR efforts.

## **PUBLICATIONS**

Finneran, J. J. and Branstetter, B. K. (2011). “Effects of noise on sound perception in marine mammals: Auditory masking and noise-induced threshold shifts,” in *Animal Communication and Noise* [in review, refereed book chapter]

Finneran, J. J. and Schlundt, C. E. (2011). "Subjective loudness level measurements and equal loudness contours in a bottlenose dolphin (*Tursiops truncatus*)," *J. Acoust. Soc. Am.* (in press). [in press, refereed]

#### **HONORS/AWARDS/PRIZES**

Chief of Naval Operations FY2010 Environmental Award